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| 14. ABSTRACT The study compared observer performance and visual search efficiency of radiologists searching for pulmonary nodules on 8-bit vs 11-bit display devices. Scope: Displays from three manufacturers were used at three sites. At each site, 6 radiologists viewed 100 chest images (half with, half without nodules) on both displays. Decisions were recorded as were viewing times and use of window/level. At one site, eye-position was recorded on a sub-set of images to evaluate visual search. Major findings: There was no significant difference in diagnostic performance as a function of display bit-depth. There was a slight viewing time advantage with the 11-bit display and the visual search data indicated it was likely due to increased efficiency in first fixating the nodules and shorter time to discriminate them from background. Time to dismiss obviously normal areas was also shorter. There was no difference in use of window/level. Conclusions: There are no significant advantages to using an 11-bit display for interpreting softcopy radiographic images. | | | | | |
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Table of Contents

| | |
|-----------------------------------|------|
| Cover..... | 1 |
| SF 298..... | 2 |
| Introduction..... | 4 |
| Body..... | 4 |
| Key Research Accomplishments..... | .5 |
| Reportable Outcomes..... | 6 |
| Conclusions..... | 15 |
| References..... | 16 |
| Appendices..... | none |

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1. Introduction

Teleradiology and PACS (Picture Archiving and Communications Systems) have changed radiology significantly over the past 20 years. [1-6] An important softcopy display issue for radiologists is monitor bit depth. Medical-grade monitors typically display 8 bits of data. This is sufficient for some interpretation tasks, but many images are acquired at higher bit depths. This results in a potentially significant *loss of information* during the diagnostic interpretation process. The problem that we investigated in this project was whether diagnostic performance would be improved with an 11-bit display compared to an 8-bit display that is comparable in every other way (e.g., maximum luminance). The major hypothesis of this proposal was that diagnostic accuracy would be higher with an 11-bit softcopy display than with an 8-bit softcopy display for the detection of pulmonary nodules in chest DR (direct digital radiography) images. The second major hypothesis was that visual search efficiency, measured using eye-tracking methods, would be greater for the 11-bit than for the 8-bit display.

2. Body

Softcopy display of images has become the norm rather than the exception. Even though softcopy reading has become fairly routine for many radiologists, there are still a surprising number of advances that are still being made with softcopy reading. One area that is crucially important in the diagnostic interpretation chain (from image acquisition through display and diagnostic viewing) is the display of image data to the radiologist. [7-8] There are still many questions about what is the optimal display method and parameters to insure the *best diagnostic interpretation*. Some of the basic questions include required spatial resolution, contrast resolution, ambient light conditions and many other environmental and display conditions. Part of the problem with answering many of these questions is that display technologies themselves are continually changing, and with each new display technology the questions need to be addressed again.

One very important display parameter issue facing radiologists today is bit depth. The majority of both commercial and medical-grade monitors (cathode-ray tube (CRT) and liquid-crystal display (LCD)) manufactured today display only 8 bits (256 gray levels) of data. This is sufficient for some radiographic interpretation tasks in which the acquired data is 8-bits or less. However, many radiographic images (e.g., computed tomography, direct radiography, full-field digital mammography) are acquired at higher bit rates (e.g., 12-14 bits). [9] This results in a potentially significant *loss of information* during the diagnostic interpretation process at the point where the radiologist views the image data on a softcopy display unit. All of the *acquired* gray levels are *not displayed* at once. The user can of course window and level while viewing the image and thus manipulate the displayed gray levels. The problem is that all gray levels are not visible at once. The radiologist takes in a huge amount of information during the initial view of the image (i.e., the initial Gestalt or global percept), so the more information available in that initial Gestalt view, the more efficient and more informative that initial impression is going to be. [10-11] Additionally, even though window and level are always options for radiologist to view more of the image data, there is no guarantee that every radiologist will use these tools with every image. More raw-image data is acquired than can be displayed on the computer display monitor.

Compounding the problem is the fact that the human visual system can detect at least 1024 gray levels, and that is well beyond the 256 available from an 8-bit display. In the past it was thought that people could see only a

limited number of gray levels, but that was with lower luminance displays. Increased display luminance in recent years may significantly increase the number of visible gray levels, making it much more important to display as many as possible. Softcopy displays capable of displaying more data bits (i.e., 11 bits) are available and can provide more data to the radiologist in one single presentation (i.e., without window/level manipulation), potentially *improving diagnostic performance*.

Another potential benefit is that providing more information in the initial image display may reduce the need for excessive windowing and leveling, reducing the time needed by the radiologist to render a diagnosis. This may reduce fatigue, an issue that many researchers have noted to be a potentially significant problem in the digital reading room [12-17]. However, with improved displays overall workflow can be improved, increasing the number of images/cases a radiologist views in a day. Fatigue from having to manipulate the image data can also be reduced significantly if the radiologist has the best possible image available in one presentation. The trade-off, of course, is that 11-bit displays are not that widely used and thus the cost now tends to be higher than 8-bit displays.

The major hypothesis of this proposal was that **diagnostic accuracy would be higher with an 11-bit softcopy display than with an 8-bit softcopy display** for the detection of pulmonary nodules in chest DR images. The second major hypothesis was that **visual search efficiency**, measured using eye-tracking methods, would be greater for the 11-bit than for the 8-bit display.

3. Key Research Accomplishments

The project had three main technical objectives. The first was to calibrate three sets display devices from three different manufacturers – one 8-bit and one 11-bit. We obtained sets of displays and video boards from three companies – DataRay, Dome/Planar and Totoku and determined their maximum and minimum luminance values after calibrating them to the DICOM standard. All monitors were calibrated within acceptable range of the targeted values.

The second objective was to carry out three independent Receiver Operating Characteristic studies using the same set of images on the three sets of monitors at each of three institutions – the University of Arizona, the University of Maryland Baltimore and the University of Southern California. The results were compared statistically for 1) differences in diagnostic performance for 8-bit vs 11-bit monitors overall, and 2) differences between monitor manufacturers (DataRay, Totoku, Dome/Planar). A set of 100 DR chest images was collected from existing databases at Arizona and Baltimore. The final set had 50 nodule-free and 50 with subtle pulmonary nodules. Nodule status was verified by computed tomography (CT). All patient identifiers were removed so the identity of the patients was not known to anyone participating in the study.

Each of the three sites recruited six radiologists to participate as observers. Each radiologist viewed all 100 images twice – once on the 8-bit and once on the 11-bit monitor. A counterbalanced presentation design was used. The task of the observers was two-fold. Their initial task was to view each image and decide whether a nodule was present or absent. They then provided their confidence in that decision using a 6-point scale where 1 = nodule absent, definite and 6 = nodule present, definite. They indicated nodule location if one was present.

The confidence data were analyzed using the statistically powerful Multi-Reader Multi-Case ROC technique (MRMC). [18] MRMC computes Az for each condition and then does an Analysis of Variance (ANOVA) on the resulting Az outputs to determine statistically significant differences between conditions. The data were analyzed overall comparing 8-bit with 11-bit (combining all the data from the 3 sites, disregarding monitor type); and separated into groups and analyzed 8-bit vs 11-bit for each display manufacturer. Whether or not they used the window/level processing function during interpretation of each case was recorded. Total viewing time was also recorded.

The third objective was to measure visual search efficiency as a function of monitor bit-depth. Visual search efficiency was measured on a sub-set of images at the University of Arizona (the only site of the three with the eye-tracking equipment) and the results compared for 8-bit vs 11-bit softcopy display. From the set of 100 images we selected a sub-set of representative images (5 lesion-free and 15 lesion-containing). We used the 4000SU Eye-Tracker with head tracker (Applied Science Labs, Bedford, MA). We used the eye-position data to characterize a number of parameters of visual search: time to first fixate a lesion, total search time, and dwells associated with each decision type (TP, FN, FP, TN). These are the parameters we have analyzed in a number of other such studies. [19-27]

4. Reportable Outcomes

a. Physical Calibration

Table 1 shows the final maximum and minimum luminance values for the three sets of monitors used in the study. The displays were calibrated following the recommendations of the DICOM Standard [28]. The target luminances were 500 cd/m^2 for the maximum and 0.6 cd/m^2 for the minimum. All monitors were within acceptable range of these targets.

Table 1. Maximum and minimum luminance values for the three sets of monitors used in the study.

| Display | 11-bit | 11-bit | 8-bit | 8-bit |
|----------------|--------------------------------------|--------------------------------------|--------------------------------------|--------------------------------------|
| | Max Luminance (cd/m^2) | Min Luminance (cd/m^2) | Max Luminance (cd/m^2) | Min Luminance (cd/m^2) |
| Planar | 500.61 | 1.00 | 504.48 | 0.84 |
| DataRay | 500.87 | 0.68 | 509.32 | 0.68 |
| Totoku | 492.35 | 0.60 | 500.45 | 0.63 |

b. Observer Performance Results

1. Overall results for all three groups/sets of displays

The observer confidence data pooled from all three displays (Totoku, DataRay, Planar/Dome) were analyzed using the Multi-Reader Multi-Case Receiver Operating Characteristic analysis [18]. There was no statistically significant difference in area under the curve (Az) performance ($F = 0.0374$, $p = 0.8491$) as a function of bit-depth of the display. Average Az with the 8-bit display was 0.8284 and average performance with the 11-bit display was 0.8253. The mean Az values for each display are shown in Figure 1. Differences between the three sites overall are likely due to differences in the observers (e.g., level of experience of the readers), although it is not possible to rule out the possibility that there are differences between the monitors themselves that contributed to the overall differences between the three sites.

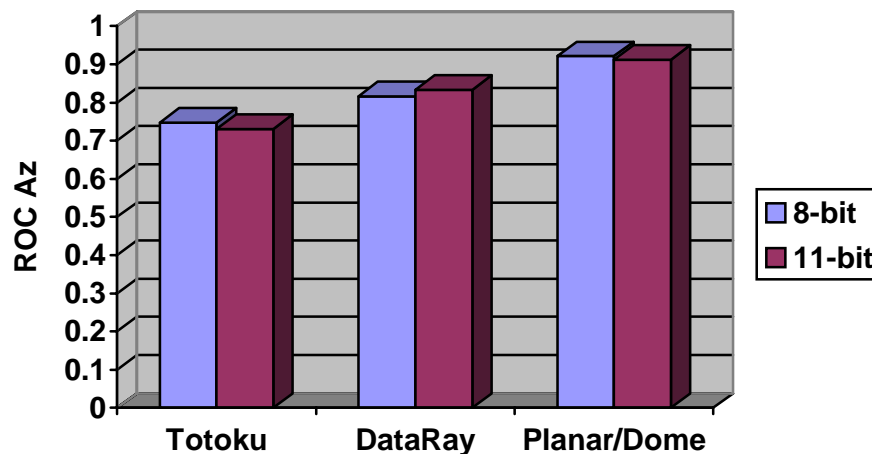


Figure 1. ROC Az values for each of the three sets of 8-bit and 11-bit monitors – Totoku, DataRay, Planar/Dome.

In terms of viewing time (i.e., time from when the image appeared on the display until they hit the next button to remove it having rendered a diagnostic decision), the data were analyzed using a repeated measures Analysis of Variance (ANOVA). There was a statistically significant difference in viewing time as a function of monitor bit-depth ($F = 10.209$, $p = 0.0014$). Although the difference was small, viewing times were significantly shorter for the 11-bit than the 8-bit displays overall. There was no difference as a function of whether or not a nodule was present or absent ($F = 0.182$, 0.6697). The average viewing times are shown in Figure 2.

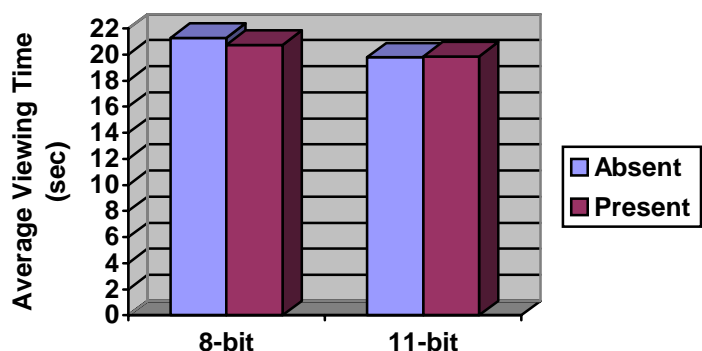


Figure 2. Average viewing time for the nodule absent and nodule present cases on the 8-bit and 11-bit displays.

The final parameter evaluated was whether or not the readers used window/level processing during the interpretation process. Overall, there was no statistically significant difference in the percentage of cases on which window/level was used ($X^2 = 1.10$, $p < 0.05$) with the 8-bit versus 11-bit display (see Figure 3). Preference for using window/level seemed to be an individual trait – some readers used window/level a lot and some readers did not, but an individual reader used it about the same with both displays.

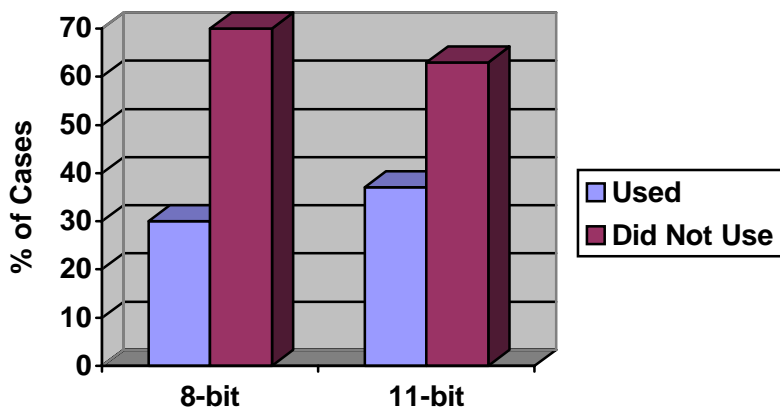


Figure 3. Percentage of times window/level was used or not used with the 8-bit and 11-bit displays.

2. Totoku display monitor results

There was no statistically significant difference in area under the curve (Az) performance ($F = 0.1860$, $p = 0.6843$) as a function of bit-depth of the display. Average Az with the 8-bit display was 0.7474 and average performance with the 11-bit display was 0.7307. The individual Az values for each observer are shown in

Figure 4. It can be seen in Figure 4 that half of the observers performed slightly better with the 8-bit and half performed slightly better with the 11-bit display. None of the individual differences were significantly different.

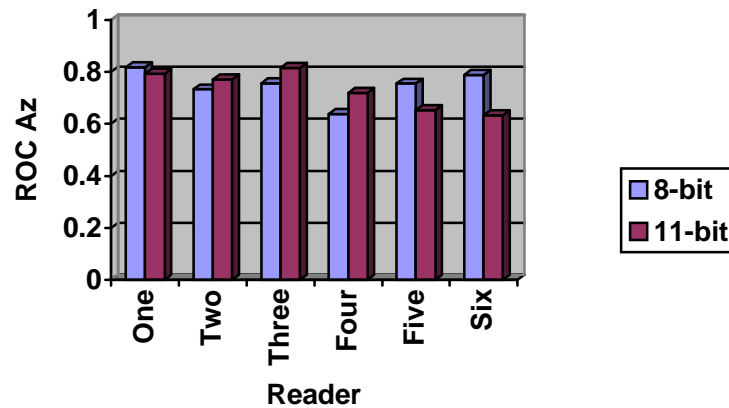


Figure 4. ROC Az values for each of the six readers using the Totoku 8-bit and 11-bit monitors.

In terms of viewing time (i.e., time from when the image appeared on the display until they hit the next button to remove it having rendered a diagnostic decision), the data were analyzed using a repeated measures Analysis of Variance (ANOVA). There was no statistically significant difference in viewing time as a function of monitor bit-depth ($F = 1.256$, $p = 0.2628$), both for nodule present and nodule absent cases ($F = 0.377$, 0.5396). The average viewing times are shown in Figure 5. The individual viewing times for the 8-bit and 11-bit Totoku displays are shown in Figure 6.

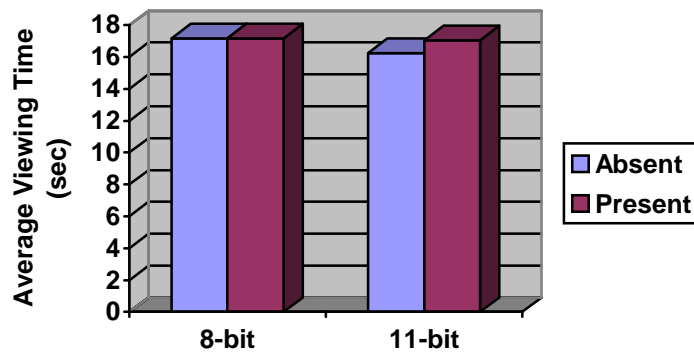


Figure 5. Average viewing time for the nodule absent and nodule present cases on the 8-bit and 11-bit Totoku displays.

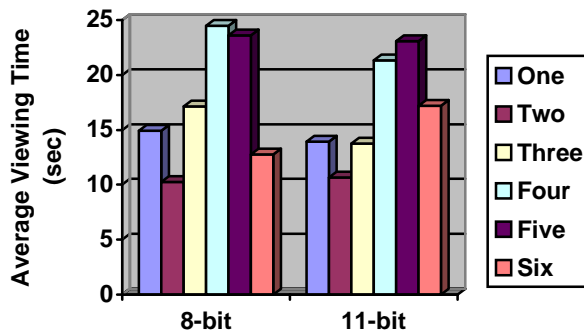


Figure 6. Average viewing time for each of the 6 readers using the Totoku 8-bit and 11-bit displays.

The final parameter evaluated was whether or not the readers used window/level processing during the interpretation process. Overall, there was no statistically significant difference in the percentage of cases on which window/level was used ($X^2 = 1.10$, $p < 0.05$) with the 8-bit versus 11-bit display. Preference for using window/level seemed to be an individual trait – some readers used window/level a lot and some readers did not, but an individual reader used it about the same with both displays (see Figure 7).

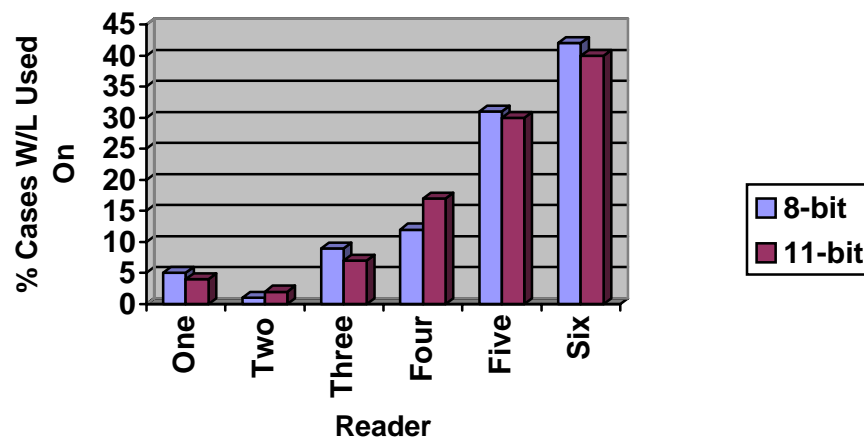


Figure 7. Percent of cases each reader used the window/level (W/L) function on with the Totoku 8-bit and 11-bit monitors.

3. DataRay display monitor results

There was no statistically significant difference in area under the curve (Az) performance ($F = 0.4613$, $p = 0.4986$) as a function of bit-depth of the display. Average Az with the 8-bit display was 0.8168 and average performance with the 11-bit display was 0.8326. The individual Az values for each observer are shown in Figure 8. It can be seen in Figure 8 that five of the observers performed slightly better with the 11-bit than with the 8-bit display. None of the individual differences were significantly different.

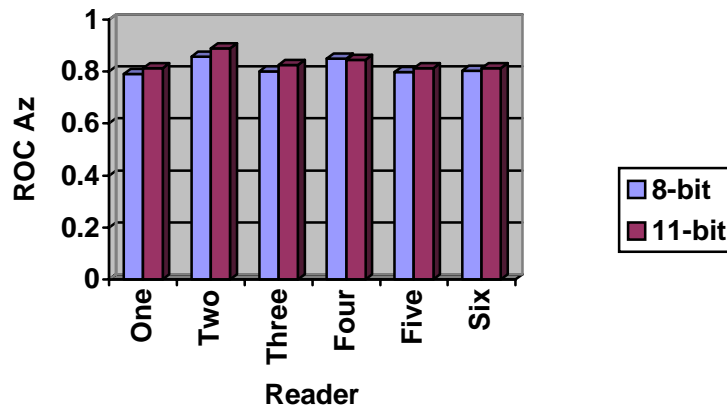


Figure 8. ROC Az values for each of the six readers using the DataRay 8-bit and 11-bit monitors.

In terms of viewing time (i.e., time from when the image appeared on the display until they hit the next button to remove it having rendered a diagnostic decision), the data were analyzed using a repeated measures Analysis of Variance (ANOVA). There was a statistically significant difference in viewing time as a function of monitor bit-depth ($F = 9.656$, $p = 0.0020$), with the 8-bit viewing taking significantly longer than the 11-bit. There was no difference as a function of whether or not the case contained a nodule ($F = 0.745$, 0.3884). The average viewing times are shown in Figure 9. The individual viewing times for the 8-bit and 11-bit DataRay displays are shown in Figure 10.

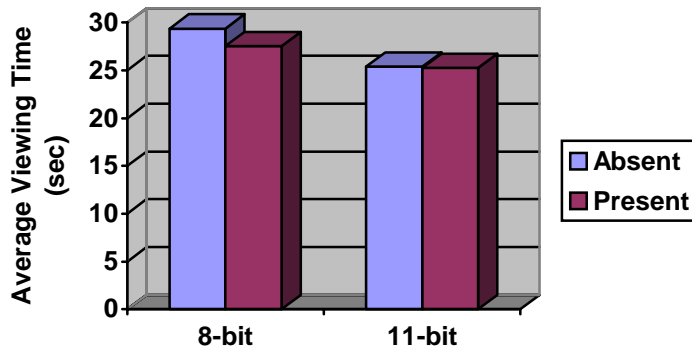


Figure 9. Average viewing time for the nodule absent and nodule present cases on the 8-bit and 11-bit DataRay displays.

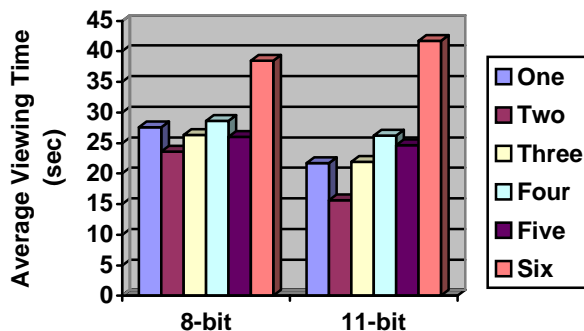


Figure 10. Average viewing time for each of the 6 readers using the DataRay 8-bit and 11-bit displays.

The final parameter evaluated was whether or not the readers used window/level processing during the interpretation process. Overall, there was no statistically significant difference in the percentage of cases on which window/level was used ($X^2 = 0.00$, $p < 0.05$) with the 8-bit versus 11-bit display. Preference for using window/level seemed to be an individual trait – some readers used window/level a lot and some readers did not, but an individual reader used it about the same with both displays (see Figure 11).

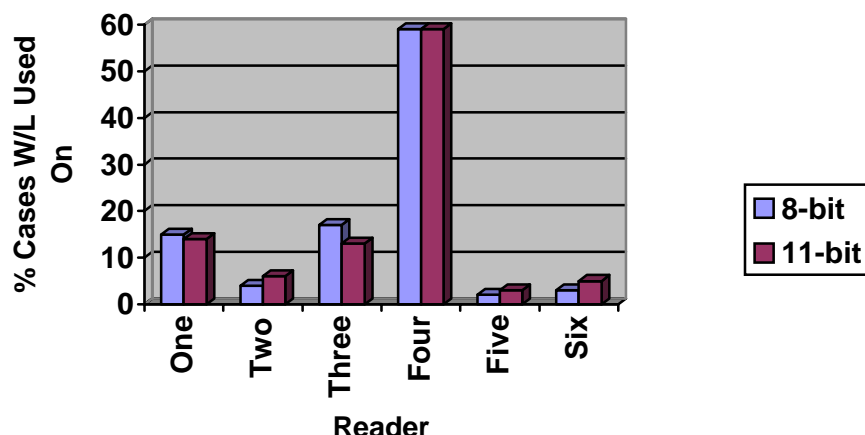


Figure 11. Percent of cases each reader used the window/level (W/L) function on with the DataRay 8-bit and 11-bit monitors.

4. Planar/Dome display monitor results

There was no statistically significant difference in area under the curve (Az) performance ($F = 0.0868$, $p = 0.7802$) as a function of bit-depth of the display. Average Az with the 8-bit display was 0.9211 and average performance with the 11-bit display was 0.9126. The individual Az values for each observer are shown in Figure 12. It can be seen in Figure 12 that two of the observers performed slightly better with the 11-bit than with the 8-bit display. None of the individual differences were significantly different.

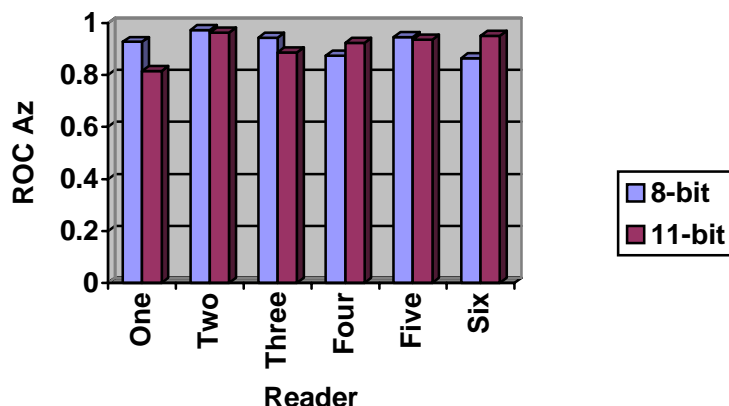


Figure 12. ROC Az values for each of the six readers using the Planar/Dome 8-bit and 11-bit monitors.

In terms of viewing time (i.e., time from when the image appeared on the display until they hit the next button to remove it having rendered a diagnostic decision), the data were analyzed using a repeated measures Analysis of Variance (ANOVA). There was no statistically significant difference in viewing time as a function of

monitor bit-depth ($F = 0.111$, $p = 0.7393$). There was no difference as a function of whether or not the case contained a nodule ($F = 0.024$, 0.8768). The average viewing times are shown in Figure 13. The individual viewing times for the 8-bit and 11-bit Planar/Dome displays are shown in Figure 14.

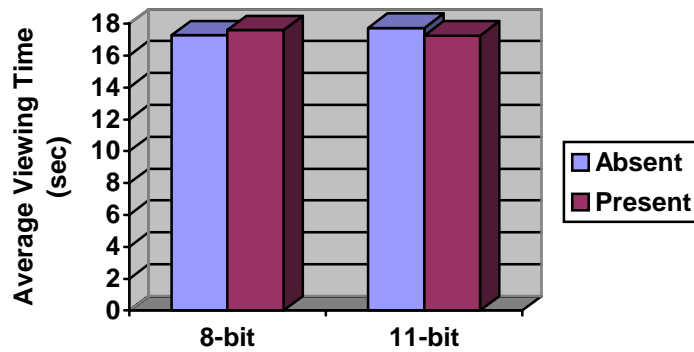


Figure 13. Average viewing time for the nodule absent and nodule present cases on the 8-bit and 11-bit Planar/Dome displays.

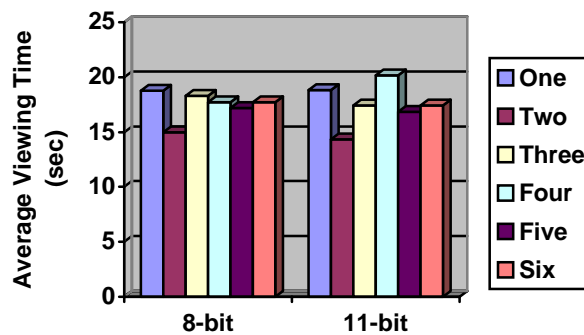


Figure 14. Average viewing time for each of the 6 readers using the Planar/Dome 8-bit and 11-bit displays.

The final parameter evaluated was whether or not the readers used window/level processing during the interpretation process. Overall, there was no statistically significant difference in the percentage of cases on which window/level was used ($X^2 = 0.00$, $p < 0.05$) with the 8-bit versus 11-bit display. Preference for using window/level seemed to be an individual trait – some readers used window/level a lot and some readers did not, but an individual reader used it about the same with both displays (see Figure 15).

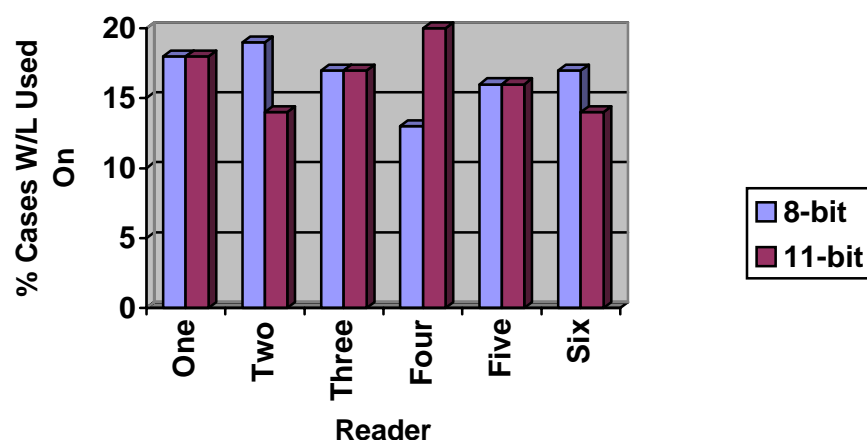


Figure 15. Percent of cases each reader used the window/level (W/L) function on with the Planar/Dome 8-bit and 11-bit monitors.

c. Visual Search Results

Six observers at the University of Arizona site viewed the set of 20 images (15 with nodules, 5 without) on the Totoku displays as their eye position was recorded [27]. Figure 1 shows a typical search pattern of one of the radiologists in the study. The circles represent fixations or locations where the eye lands with foveal (high resolution) vision. The size of the circle represents shorter (smaller) or longer (larger) dwell times. The lines connecting the circles represent saccades, or jumps, between the fixations and indicate the order in which the fixations were generated. The arrow in Figure 1 indicates the location of the nodule. In this case the radiologist fixated the nodule and reported it correctly (a true positive decision).

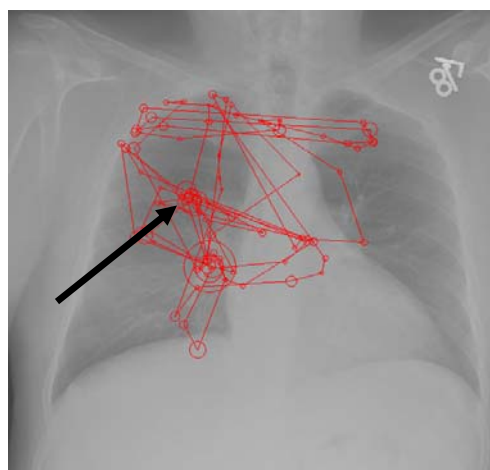


Figure 1. Typical scanning pattern of a radiologist searching for pulmonary nodules. The arrow indicates the location of the nodule.

In terms of total viewing time (time from when the image first appears until the observer hits the “next” button and it is removed), it took slightly less time on average for the observers to view the images with the 11-bit display (5.78 sec vs 6.21 sec) but the difference was not statistically significant ($t = 1.009$, $p = 0.3151$). Figure 1 shows the average total viewing times for the individual observers in both reading conditions.

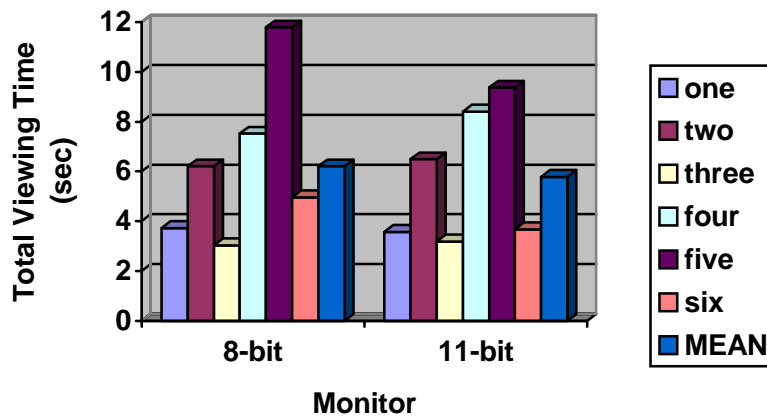


Figure 1. Mean total viewing time for the individual readers using 11-bit vs 8-bit displays. The mean is shown as well.

The next eye-position parameter evaluated was time to first hit the nodule targets with foveal (high resolution) gaze during the search of the image. The results for the true positive (TP or when they correctly reported the nodule as present) and false negative (FN or when they did not report a nodule that was present) decisions are shown in Figure 2. For both TP and FN decisions, time to first hit the nodules was shorter with the 11-bit than the 8-bit display. When tested with an Analysis of Variance (ANOVA), there were, however, no statistically significant differences as a function of bit-depth ($F = 0.981$, $p = 0.3234$) or decision ($F = 0.002$, $p = 0.967$).

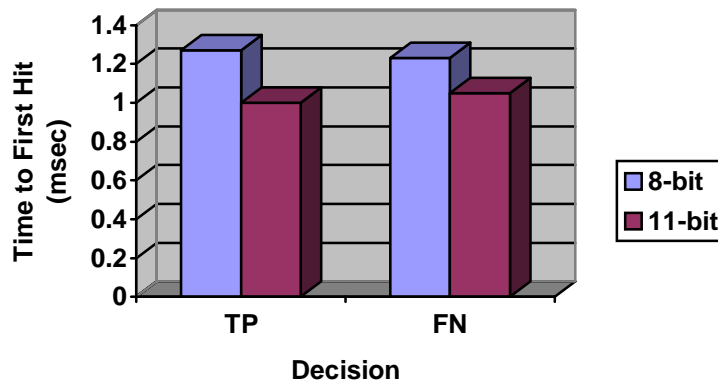


Figure 2. Average time to first hit a nodule (msec) for true positive (TP) and false negative (FN) decisions.

The third eye-position parameter evaluated was cumulative dwell times associated with each decision type. Briefly, the system samples the eye position of the reader every 1/60 second and assigns an x,y coordinate in image space (the head tracker data are integrated in real-time with the eye-position data). The x,y coordinates are then grouped into fixations using a running mean distance calculation. Fixations can then be grouped in clusters, which can be thought of as a circular area of about 2.5 degrees radius with its center at the mean x,y location of the group of fixations contributing to the cluster. Cumulative clusters can be calculated by combining clusters generated when a reader re-fixates the same image area (at any point during search). The location of the clusters can be used to associate dwell times with decisions. True positives and false negatives are defined by the lesion locations and any cluster that overlaps the lesion location by at least 50% is considered a "hit". False-positive locations will be specified by the readers so we will be able to use the same "hit" criteria for these decisions. True negative decisions constitute areas that are lesion free and receive fixation clusters.

The average cumulative dwells for true positive (TP), false negative (FN), false positive (FP) and true negative (TN) decisions are shown in Figure 3. It can be seen that for the 11-bit display, cumulative dwell times for each decision category were lower than for the 8-bit display. When tested with t-tests for paired observations, the TP ($t = 1.452$, $p = 0.1507$), FN ($t = 0.050$, $p = 0.9609$) and FP ($t = 0.042$, $p = 0.9676$) were not statistically significant. The difference for the TN decisions was statistically significant ($t = 1.926$, $p = 0.05$).

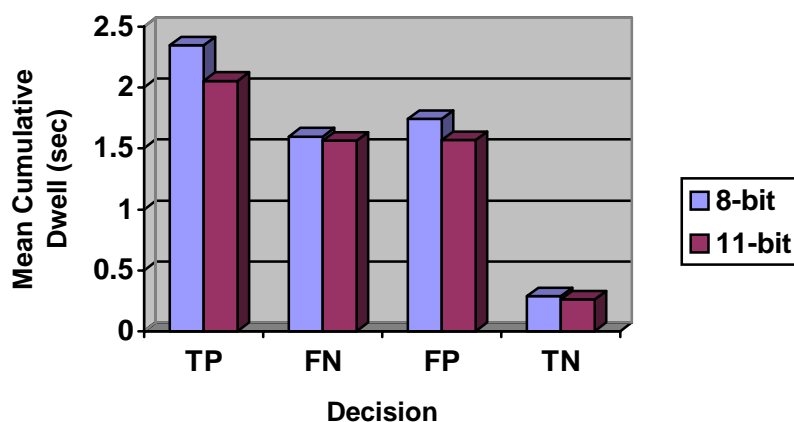


Figure 3. Mean cumulative dwell times (sec) for TP, FN, FP and TN decisions.

5. Conclusions

Overall, there was no statistically significant difference in observer performance (as measured by ROC Az) as a function of bit-depth for any of the three displays devices used at the three sites. Some observers performed slightly better with the 8-bit and some with 11-bit, but even on an individual basis there were no differences due to display bit-depth. Performance overall varied from site to site and that could be due either to differences between the observers at the three sites or possibly differences between the three sets of monitors that had nothing to do with bit-depth. Although all three sets of displays were set to approximately the same maximum and minimum luminance values and calibrated to the DICOM GSDF Standard, the technology used in each display is different and thus could lead to potential differences in performance. Further investigation of some of the other physical characteristics of the displays could be done in the future to determine if such differences exist.

There was a statistically significant difference in overall viewing time as a function of display bit-depth, although the actual time difference of 1-2 sec is relatively small. The DataRay displays were the main contributor to this effect although for all three sites there was a slight time advantage with the 11-bit display. Small differences in viewing time may contribute to improved workflow when one considers the very large number of images a radiologist views each day, but those in the range of 1-2 sec observed in this study seem unlikely to affect workflow in a practical sense.

The use of window/level did not differ significantly as a function of display bit-depth. It was hypothesized that since the 8-bit display showed fewer gray levels compared to the 11-bit display, the observers would have to window/level more with the 8-bit display to visualize all the gray levels. This was not the case. Although one could see the effects of reduced bit-depth when a simple geometric pattern (step-wedge) was shown on the displays, when a complex images without regular, definable edges was shown it was generally impossible to see any differences. The use of window/level seems to be more of a personal preference than a function of display bit-depth. Some radiologists use it a lot and some rarely use it.

The eye-position study, although conducted at only one of the sites (Totoku displays) revealed some interesting differences in visual search efficiency that correspond to the observation at all three sites that total viewing time was slightly more efficient with the 11-bit displays. Although not statistically significant, time to first fixate (direct the axis of high resolution foveal gaze) on the nodule, whether reported or not, was shorter with the 11-bit than 8-bit display. This suggests that the nodules were more visible and thus attracted attention earlier in search with the 11-bit display. As with total viewing time, however, the lack of statistical significance makes it difficult to determine if these relatively small differences would actually impact workflow. The time to render a positive decision (true or false) was also shorter with the 11-bit display, again suggesting that it may have been easier to discriminate the nodule from the background with the 11-bit display. The false negatives (missed nodules) actually attracted more viewing time with the 11-bit display than with the 8-bit, adding credence to the idea that nodules were more conspicuous or visible with the 11-bit display. The observers were attracted to these more visible features even though they did not resolve into the correct perception of a nodule being present. The true negative decisions, which constitute the majority of clusters generated during search of an image, were significantly shorter for the 11-bit display, again suggesting a potential improvement in search efficiency with the 11-bit display.

Although there may be a slight advantage with an 11-bit display compared to an 8-bit display in terms of overall viewing time and visual search efficiency, the differences are relatively small and in a practical sense do not seem likely to affect daily workflow in a significant manner. The general lack of differences in diagnostic performance for any of the three displays tested suggest even more strongly that an 11-bit display does not provide a significant advantage over an 8-bit display. Since 11-bit displays are typically more expensive than the more traditional 8-bit displays and generally require a special video board at an additional cost, the results of the present study indicate strongly that there is no practical advantage to using an 11-bit display. This study was limited to chest images with subtle pulmonary nodules, but it seems unlikely that other types of images with other lesions are likely to yield significant differences in diagnostic or search behavior as a function of monitor bit-depth. Confirmation of this would certainly require future studies.

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